SYSTEM OF MULTIPLEX TELEPHONY BY THE USE OF VACUUM TUBES

BY

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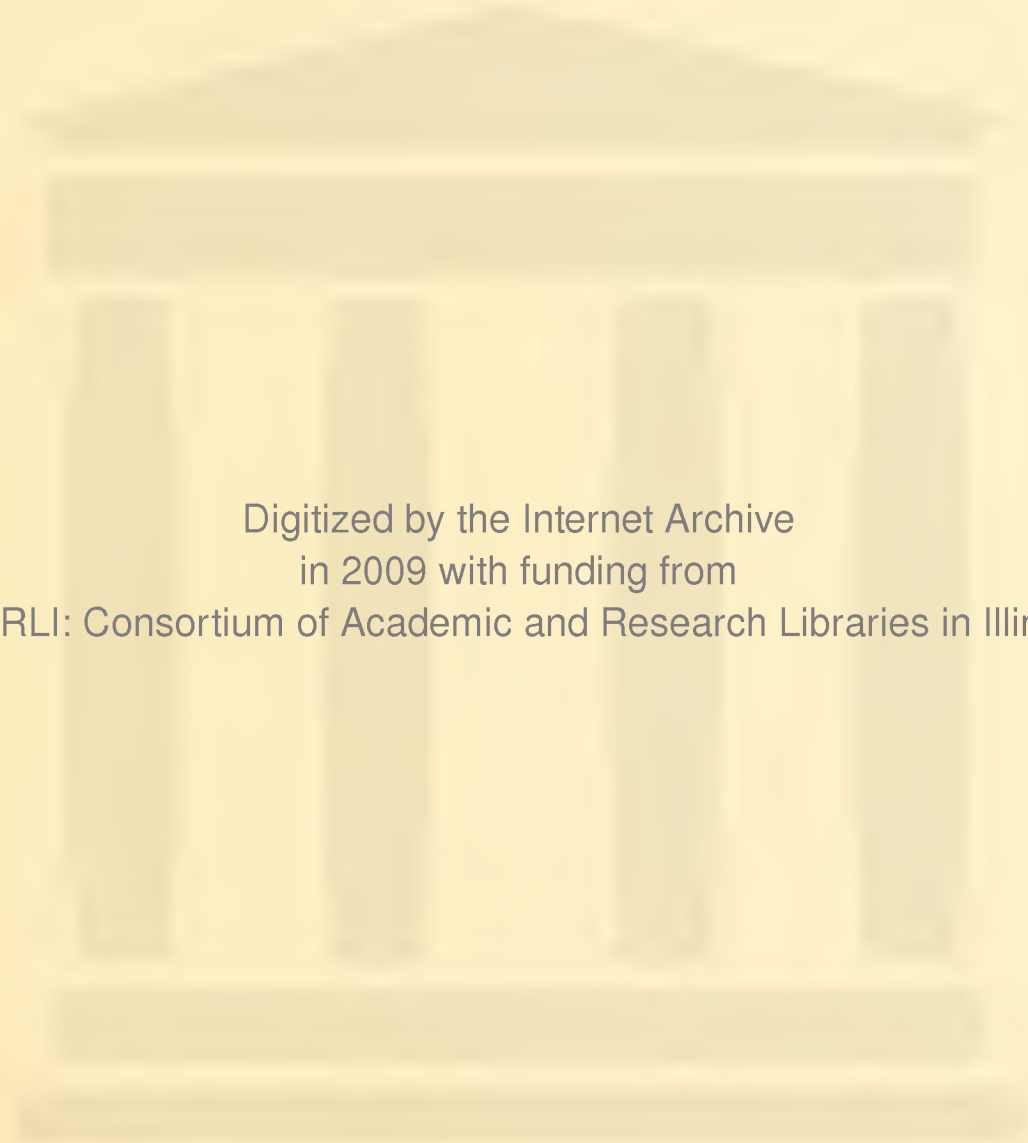

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A System of Multiplex Telephony by the Use of Vacuum Tubes

A THESIS

PRESENTED BY

E. H. ARNOLD AND A. R. THROOP

TO THE

PRESIDENT AND FACULTY

OF

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FOR THE DEGREE OF

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IN

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MAY 29, 1919

APPROVED

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OBJECT

The object of this thesis is to develop a system of multiplex telephony, to transmit without interference, simultaneously, several telephonic messages over a single pair of wires; one transmitting and one receiving medium at each end of the line for each circuit. The sources of high frequency current are to be circuits operating by virtue of the characteristics of vacuum tubes.

PART I

Previous Investigations
and
The General Problem.

The first work in this direction was done by Major Geo. O. Squier of the Signal Corps, United States Army. A report of his work was given in the Proceedings of the American Institute of Electrical Engineers of June, 1911, and later in several other of the electrical journals. According to the article published in Telephony of January 14, 1911, the following is said of the patents issued to the Major.

"These patents are dedicated to the public use, and the invention may be used without royalty by the government or any citizen of the United States."

When these investigations were made, the limited methods for the generation of undamped high frequency current made further experimental work impossible. The cost of one transmitting apparatus

alone was almost prohibitive, and therefore nothing more was done with the idea until very recently. The following is an extract from the patents issued to Major Squier.

"By employing ultra-sound electromagnetic wave frequencies as the vehical for transmitting telephonic and telegraphic messages, it is evident that all harmful effects to any element of the battery telephone apparatus are immediatly removed, since not only are such effects very minute in character, by virtue of the high period of oscillations, but also, even if there were any effects in the telephone receiver, or transmitter, or any part of the apparatus, it could not be detected by a human being, since the natural limitations of the ear afford a most sensitive and sure separation between all frequencies above I5,000 to 20,000 and down to I6 per second, which is the lower limit of audibility. Therefore, a fundamental principle of this system may be said to be, from one viewpoint, the utilization of this unalterable

characteristics of the human ear."

"With such frequencies as are used in ordinary battery telephony the so called skin-effect is comparatively small, and the current is fairly well distributed throughout the cross section of the conductor. As the frequency increases the skin - effect becomes more pronounced and the energy appears to be more and more transmitted or stored in the ether surrounding the conductor. For this reason the battery telephone current is largely conduction current thru metal, and the ohmic resistance of the wire is one of the principle elements which limits long distance telephony at present, whereas in commercial wireless telegraphy, in which frequencies from 100,000 to several million are used, the impressed energy is chiefly radiated into the surrounding ether."

"In the intermediate range from say 20,000 to 100,000 and above, the energy is largely carried by the ether, but is still sufficiently linked to the conductor to prevent excess radiation into

the ether. The conductor, while carrying but a small part of the energy at its surface, nevertheless acts as a sufficient guide for the high frequency electromagnetic waves. In accordance with these principles, use is made of these efficiently guided ether waves as a vehical to carry the telephonic or telegraphic messages."

Since a number of high frequency waves of different frequencies may be impressed on the same line, and since these may be selectively separated from each other by suitably tuned circuits, it appears that multiplex telephony may be accomplished in this manner. It should be noted however that the entire success of such a system rests upon the possiblity of bringing two circuits, one at each end of a line, into resonance; that is, that they have the same frequency of current oscillation. The expression for this frequency is $N = \frac{1}{2\pi\sqrt{LC}}$, where L is the inductance in henries and C is the capacity in farads. The equation neglects resistance, which can be made very small in an actual

circuit. The line circuit however does contain considerable resistance, and therefore the equation $N = \frac{I}{2\pi}\sqrt{\frac{I}{LC} - \frac{R^2}{4L^2}}$ applies. In which case R is the effective resistance.

This brings up the question of critical resistance. If R is equal to $2\sqrt{\frac{L}{C}}$ the equation shows that the circuit will be just oscillatory; if greater than this value the discharge of the condenser will not be oscillatory, but if less, the circuit will function as desired. Therefore if the success of this system imposes the necessary condition that the line circuit oscillate, then the limitations are immediatly apparent, for the line resistance R is constant and hence circuits of such frequency that $R > 2\sqrt{\frac{L}{C}}$ cannot be employed. To a certain extent a circuit not in resonance with another may be forced if there is sufficient energy present, but beyond this limited deviation no oscillations persist.

A typical circuit used by Major Squier is shown in Fig. I. The high frequency apparatus is

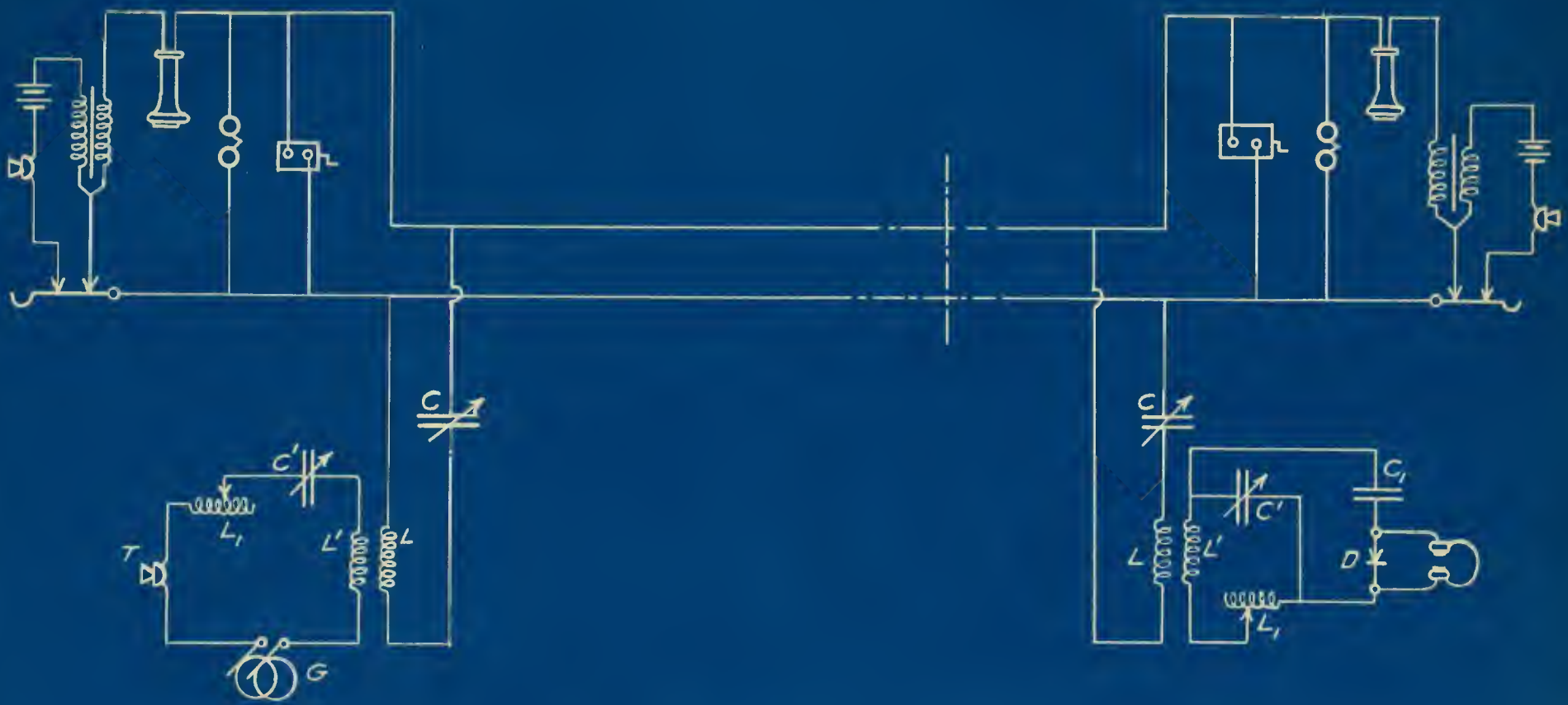

FIG. 1

"MULTIPLEX TELEPHONY BY MEANS OF ELECTRIC WAVES GUIDED BY WIRES"

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bridged directly across the line of a local battery telephone circuit. The local circuit consists of a transmitter in series with a battery and primary of a telephone induction coil. The receiver is in series with the secondary of the coil and the line. Across the line is bridged a 1000-ohm ringer and hand generator.

A high frequency inductor type alternator G is used to supply the high frequency currens which is led thru the transmitter T. In this manner the amplitude of the wave is changed, due to the varying resistance of the transmitter under the action of sound waves. The variable condenser C^I and inductances L^I and L_I determine the constants of the primary oscillating circuit. The capacity and inductance is made such that the circuit has a natural period equal to the frequency of the alternating current generated by the machine. The line is also made to oscillate with this frequency by adjusting the condensers C. The inductance L is added to the natural inductance of the line and also

serves to couple the line to the transmitting and receiving oscillating circuits.

At the receiver end a similiar coupling is made to a circuit very similiar to those commonly used in wireless telegraphy. The frequency to which the receiver circuit will respond is determined by the values of C' and L' and L_I added together. The receivers are bridged around a crystal detector D_I, which in turn is bridged thru a fixed condenser C_I to the oscillatory circuit. The detector D has only unilateral conductivity, hence for every change in the magnitude of the high frequency wave the condenser C_I receives a charge, and immediatly upon a second variation , discharges into the receivers.

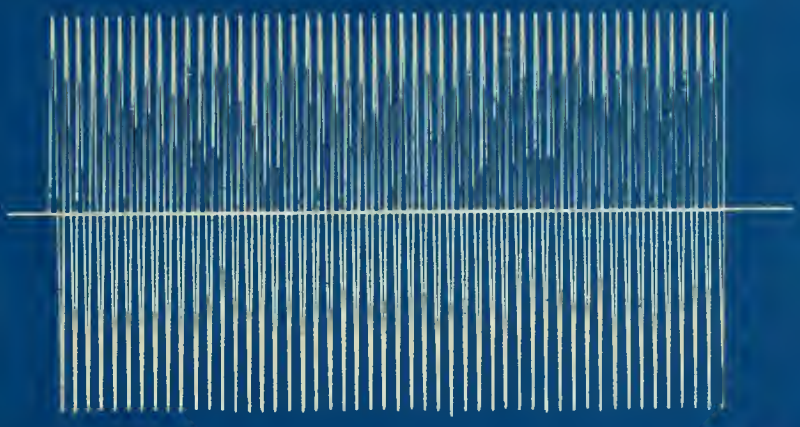
The condensers C are of radio dimensions, that is, an alternating current cannot pass thru them unless it has a frequency above the audible limit of about 20,000 cycles per second. Therefore it is evident that speech frequency cannot enter the radio frequency circuit, and since the radio

frequency is beyond the audible limit, the two circuits shown may function without interference.

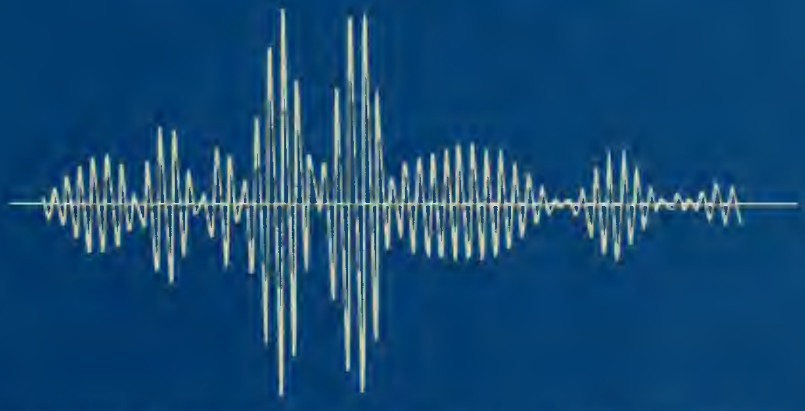
The modulation of a high frequency current is accomplished by varying the amplitude of the wave but not its frequency. Fig.2 serves to illustrate the idea. The upper figure represents the oscillogram of a voice current in an ordinary telephone circuit. Such a current has a frequency of from 500 to 2,000 cycles per second. The difference in magnitude of the succeeding waves is due to the varying resistance of the transmitter under the action of sound waves. The middle figure shows a high frequency current of constant amplitude and having above 20,000 cycles per second. The lower figure represents the audio frequency superposed upon the radio or high frequency. It is seen that the frequency is not changed, but merely the amplitudes.

In the experiment as here described, the alternator was run at such a speed as would produce current at a frequency of 100,000 cycles per second.

VOICE-CURRENT IN A TELEPHONE CIRCUIT



A HIGH-FREQUENCY CURRENT



HIGH-FREQUENCY CURRENT MODULATED
TO TRANSMIT A VOICE-CURRENT.

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FIG. 2

The inductances and capacities were those ordinarily employed in radio work. Using the circuit shown in fig. I, the inventor claims that absolutely no interference was noticeable and that two conversations were carried on simultaneously.

The purpose of our work is to repeat these results, and to develop a combination receiving and transmitting circuit, which may then be duplicated at various frequencies to accomplish multiplex telephony. High frequency is to be generated by means of electron tubes, and the receiving circuit is also to function by virtue of the characteristics of this apparatus.

In its 1918 report to the stockholders, the American Telegraph and Telephone Company announced the success of a multiplex system in which five conversations are carried on simultaneously. The details of this system and the circuits used are entirely unknown to us at the time of this experimental investigation.

To begin the discussion of our work we will give an outline of the operation and characteristics of the electron or vacuum tube, which has revolutionized all systems for the transmission of intelligence.

PART 2

Thermionic Conduction

The conduction of electricity between two electrodes maintained at a difference of potential is the immediate result of the flow, or passage, of free electrons within the conducting medium. In the structure of ponderable matter, electrons are always associated with nuclei, and together they form the normal ultimate division of matter - the uncharged atom. When a normal atom is separated from an electron, ionization is said to have occured, and the resultant or remaining atom has positive characteristics.

Mr. Mills, of the Western Electric Company, defines a vacuum as, " A space free from dislodged molecular or atomic masses." If this be accepted, then a vacuum admits of the presence of electrons, since electrons are the dissociated ions of an atom. From this we may say that gases and vapors are conducting only by the action of an ionizing agent or by being supplied with electrons at the cathode.

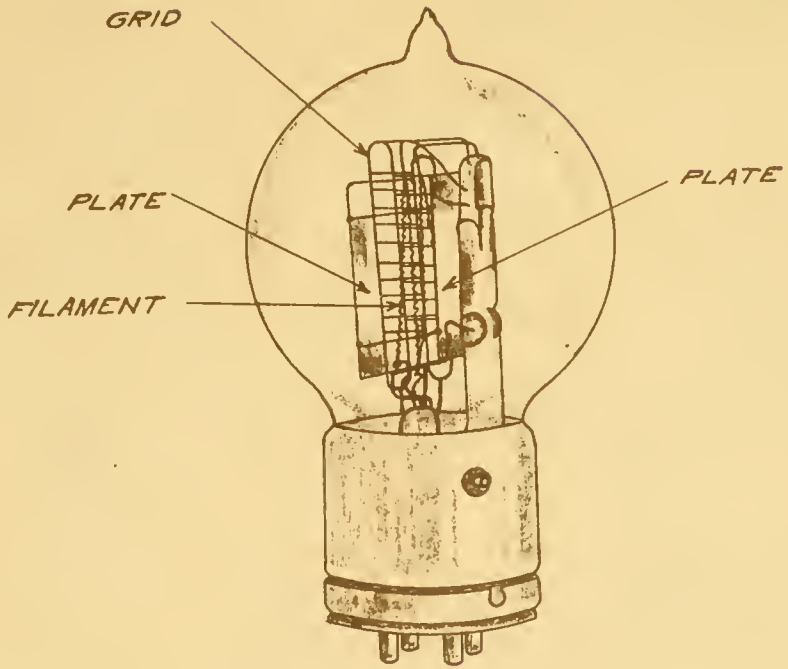
or ions at the anode. Ionization is possible under a number of conditions, but the method in which we are interested is ionization by incandescent substances. By this method the free electrons in a metal are made available.

Conduction thru a vacuum can only occur thru the presence of electrons and their flow from cathode to anode. Since the electrodes must be physically sealed in the walls of the vacuous space, a necessary condition is that the electrons must be emmitted from the cathode itself. The metal cathode may be made to emit electrons by incandescence, and conduction started as soon as a difference of potential is applied. Should there be an appreciable amount of gas in the otherwise vacuous space, the electrons emitted from the heated cathode strike the atoms of the gas and liberate other electrons. This is called ionization by collision. In the tubes made by the Western Electric Company the residual gas is so small in quantity that ionization by collision may be disregarded, and conduction considered due only to the electrons emitted by the heated cathode.

Vacuum Tubes

In this investigation two types of tubes were used, both of which are made by the Western Electric Company for use in the radio work of the Signal Corps. They were designated by that organization as the VT-I and the VT-2. The VT-2 is intended for use as a generator of high frequency oscillations, and the VT-I as a receiver. However, these tubes will function very well for either purpose.

The construction is shown by the sketches of Fig. 3. Both tubes have three elements; the filament, grid, and plate. The filament, in the center of the inside structure, constitutes the cathode and terminates on two of the connecting pins in the base. The anode consists of two metal plates mounted by supporting wires, one plate on each side of the filament. The third element is the so called grid. It is a wire framework across the sides of which are stretched fine wires, the whole completely enclosing the filament.



TRANSMITTING TUBE
VT-2

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RECEIVING TUBE
VT-1

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FIG. 3

In this way each side of the grid is between the filament and one of the plates. A vertical glass rod supplies the lateral support for the structure. The VT-I has a similiar inside construction, and therefore only the shape of the bulb and base has been illustrated. The plates are cut or punched from sheet steel. The filament is of twisted platinum strip coated with a thermionically active compound. The grid is often made of punched sheet steel also, otherwise the cross wires are of tungston. The base consists of a metal shell with a phenol-fibre diaphram at the bottom carrying the connecting studs. The entire interior of the base is filled with insulating wax.

In conduction thru gaseous media, current does not flow according to Ohm's Law. A series of tests upon these tubes was performed in order to determine the characteristics; that is, the effect upon conduction of a change in heating of the filament, a change in potential of the anode or plate, and the results obtained by putting upon the grid, charges of both positive and negative polarity of different

magnitudes.

These tubes were made to meet the specifications laid down by the Signal Corps; and therefore with a given set of data for the three elements of the tube, certain results should be expected.

The normal filament current of the VT-I is I.I amperes. The plate potential is between 25 and 30 volts. The average tube has an amplification of 200 and an average life of 500 hours.

The normal filament current of the VT-2 is I.36 amperes at 7 volts. The plate voltage is between 250 and 300 volts, and the high frequency output to be expected is from 3 to 5 watts. The latter figure is low, I0 watts having often been drawn without heating the plates red.

Vacuum tubes are also known by their amplification constant u. "It is the ratio of that change in plate voltage which produces a given change in plate current to the change in grid voltage to produce the same change in plate current.

The circuit used for making these tests is shown in Fig. 5, and the instruments used are as follows,

A_I , 0-I500 milliammeter, Weston No. 2338

A_2 , 0-50, 0-500 milliammeter, Keystone No. I8245.

V_I , 0-I5, 0-I50 voltmeter, Weston No. 4405 or 0-300, 0-750 voltmeter, Weston No. 4607.

V_2 , 0-I5, 0-I50 voltmeter, Weston No. 4337

R is a current rheostat, and PR is a potential rheostat. A reversing switch was included in order to reverse the polarity of the grid potential.

The VT-I tube was tested first and the data obtained are tabulated herewith. The values show up clearly what has taken place when plotted as shown in Fig's. 6,7 and 8. In Fig. 6 we have the plate current plotted against the plate voltage for three values of filament current. The departure from Ohm's Law is evident, and it is also seen that the curve showing the relations of these variables is largely dependent upon the number of electrons present in the vacuum; since the latter is dependent

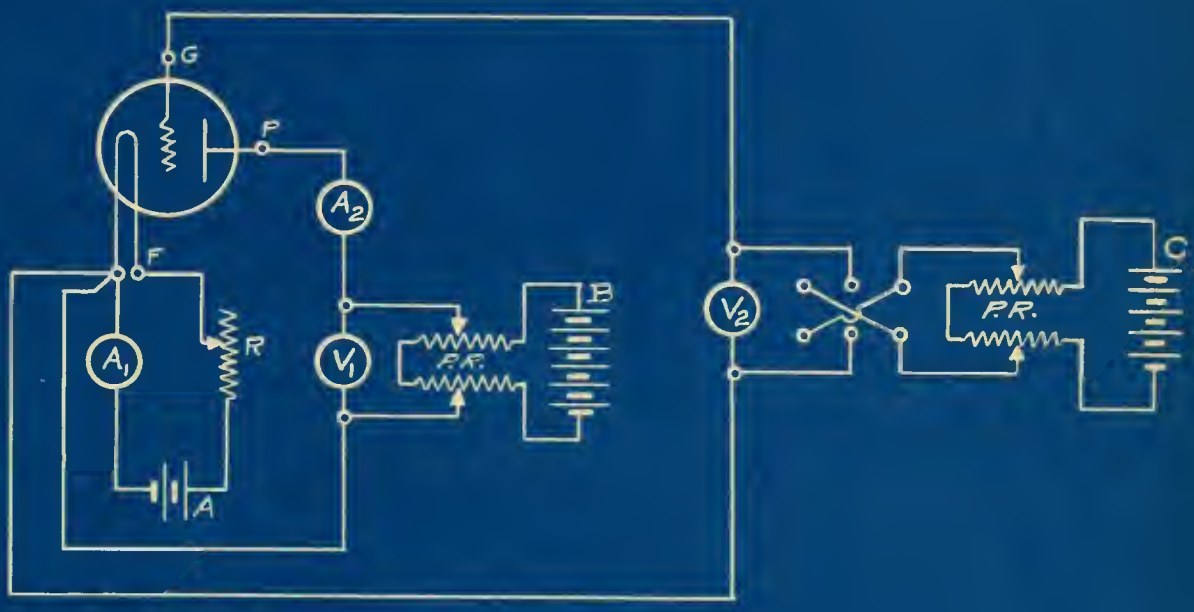

FIG. 5

CIRCUIT FOR DETERMINATION OF VACUUM TUBE CHARACTERISTICS

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VACUUM TUBE DATA

Characteristics of VT-I

Grid potential zero

Plate potential Volts	Fil .9 Plate current Milliamperes	Fil I.I Plate current	Fil I.3 Plate current
I0	.20	.I0	.I0
20	.40	.40	.45
30	.90	I.I0	I.20
40	I.60	I.90	2.00
50	2.25	2.80	3.I0
60	2.75	3.75	4.25
70	3.20	4.70	5.35
80	3.50	5.80	6.60
90	3.70	6.80	7.90
I00	3.95	7.80	9.30
II0	4.I0	9.I0	I0.80
I20			I2.35

Characteristics of VT-I

Plate current, Milliamperes.	Grid voltage	Plate current, Milliamperes.	Grid voltage.
Plate voltage 30		Plate voltage 60	
Fil. Curr. I.I		Fil. Curr. 0.9	
0.00	-6.3	0.0	- 9.0
.25	5.0	.25	8.0
.85	3.5	.85	6.0
I.55	2.0	I.70	4.0
2.45	0.5	2.45	2.0
2.75	0.0	2.80	0.0
3.00	+ 0.5	3.25	+ I.0
3.90	2.0	3.60	3.0
4.85	3.5	3.85	5.0
6.00	5.0	4.I5	7.0
6.90	6.5	4.40	9.0
8.00	8.0	4.60	II.0
8.90	9.5	4.80	I3.0
9.80	II.0		
I0.95	I2.5		

Characteristics of VT-I

Grid potential zero.

Filament Current, Milliamperes.	Milliamperes Plate current B_v=30	Plate current B_v=60	Plate current B_v=90
750	.50	.60	.50
800	.70	I.I0	I·00
850	.80	I.70	I.90
900	I.00	2.35	2.95
950	I.I0	2.90	4.I0
I000	I.I5	3.25	5.00
I050	I.I5	3.45	6.00
II00	I.I5	3.70	6.65
II50	I.I5	3.80	6.95
I200		3.90	7.25
I250		4.00	7.40
I300		4.I0	7.65
I350		4.I5	7.85

Characteristics of VT-2

Grid potential zero

Fil.I.36 Plate V. = 300

Plate potential Volts	Plate current Milliamperes.	Fil. Current milliamperes.	Plate current Milliamperes.
75	4.6	950	35.0
90	7.6	I000	40.0
I05	I0.0	I050	46.0
I25	I3.5	II00	56.0
I45	I7.6	II50	6I.0
I60	20.8	I200	62.0
I80	25.7	I250	63.0
200	30.5	I300	64.0
220	35.5	I350	64.0
240	4I.4	I400	65.0
260	47.0		
280	54.0		
300	60.0		

Characteristics of VT-2

Plate V.= 300

Fil. = I.36

Grid potential Volts	Plate current Milliamperes
- 70	4.6
60	4.7
50	4.8
40	6.2
30	I2.5
20	24.0
I0	42.0
5	53.0
0	64.0
+ I0	84.0
20	II0.0

upon the heating of the filament and hence upon the filament current. The excellent construction of the tube is evidenced by the curve for a filament current of I.I amperes, the specifiec value. In this case the relation closely approaches a straight line.

In fig.7 the plate voltage was held constant and the filament current was made the independent variable. For a plate voltage of 30, saturation is well established at a filament current of I.I amperes, and a slight change in this value does not seriously effect the results expected. While, with a plate voltage of 60 the plate current curve is at an unstable point and poor results are obtained. Both Fig. 6 and 7 give illustrations of the saturation phenomenon.

The most important characteristic of the tube is shown in Fig.8, for here is illustrated the amplifying feature. Two conditions are set up, one for the specified values of the tube, and the other with other values. With the grid at zero potential, a plate current of 2.8 milliamperes is found to flow, when the filament current was I.I

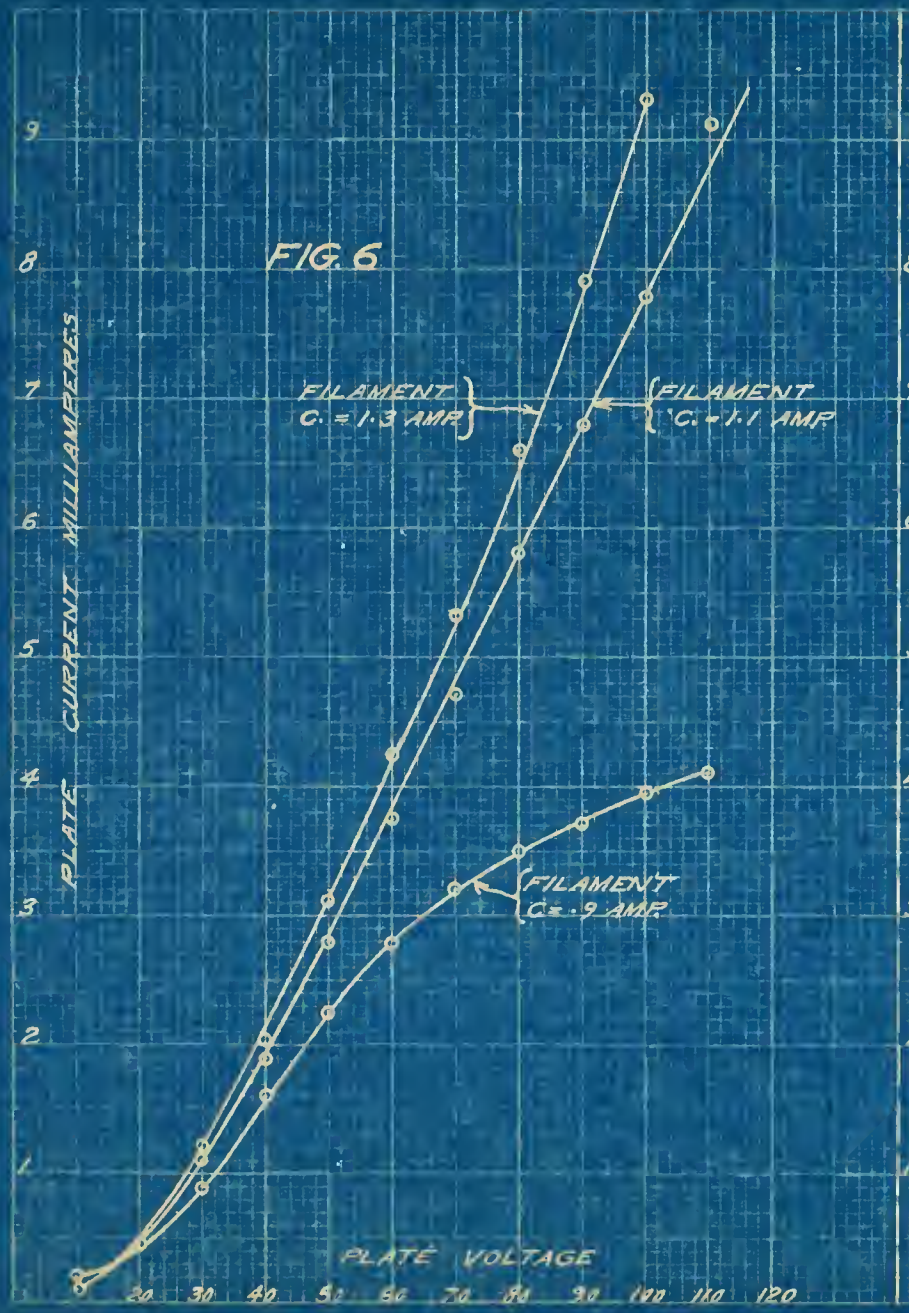
FIG. 6
PLATE CURRENT MILLIAMPERES
FILAMENT C. = 1.3 AMP.
FILAMENT C. = 1.1 AMP.
FILAMENT C. = .9 AMP.
PLATE VOLTAGE
20 30 40 50 60 70 80 90 100 110 120

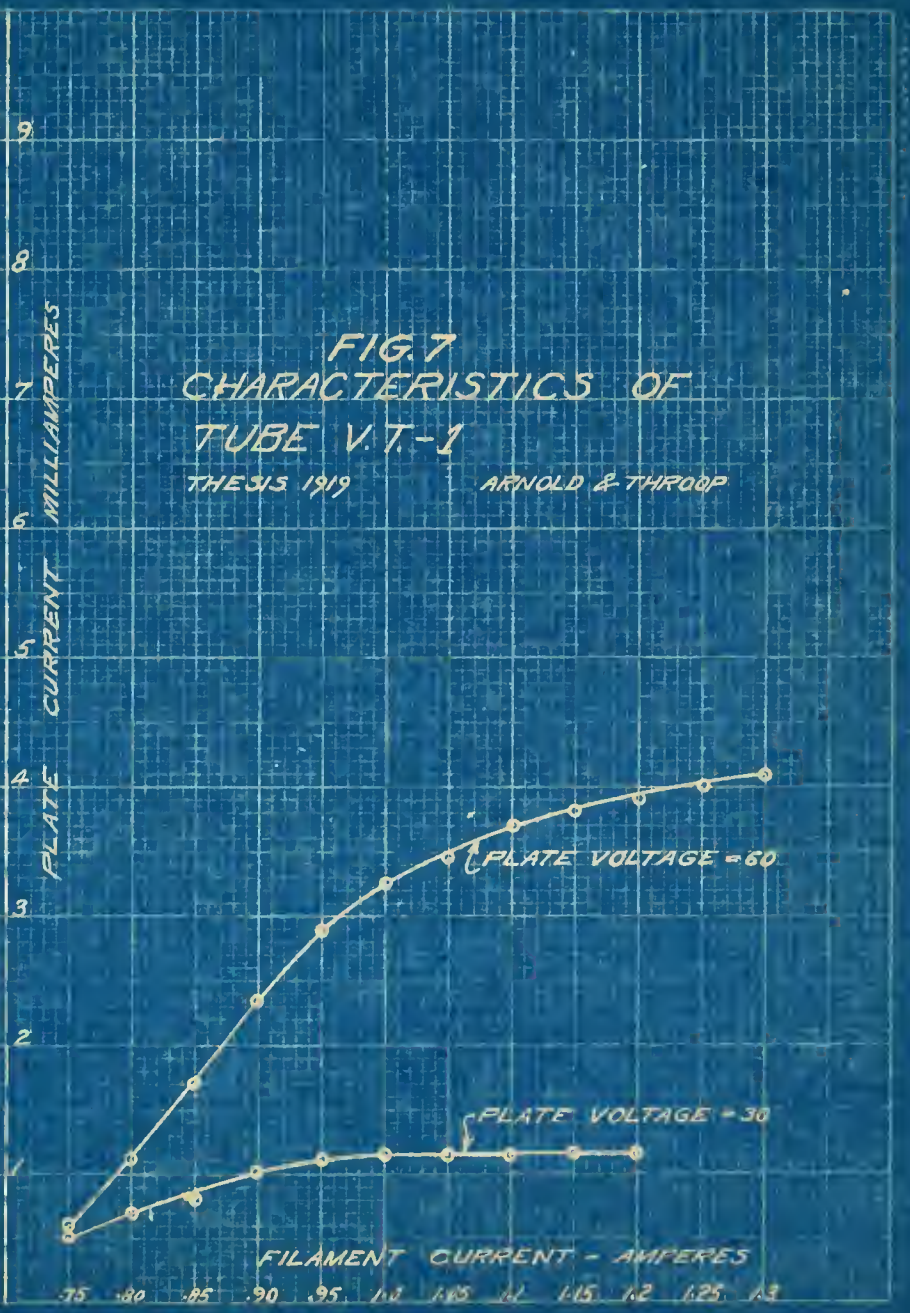
FIG. 7
CHARACTERISTICS OF TUBE V.T.-1
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PLATE CURRENT MILLIAMPERES
PLATE VOLTAGE = 60
PLATE VOLTAGE = 30
FILAMENT CURRENT - AMPERES
.75 .80 .85 .90 .95 1.0 1.05 1.1 1.15 1.2 1.25 1.3

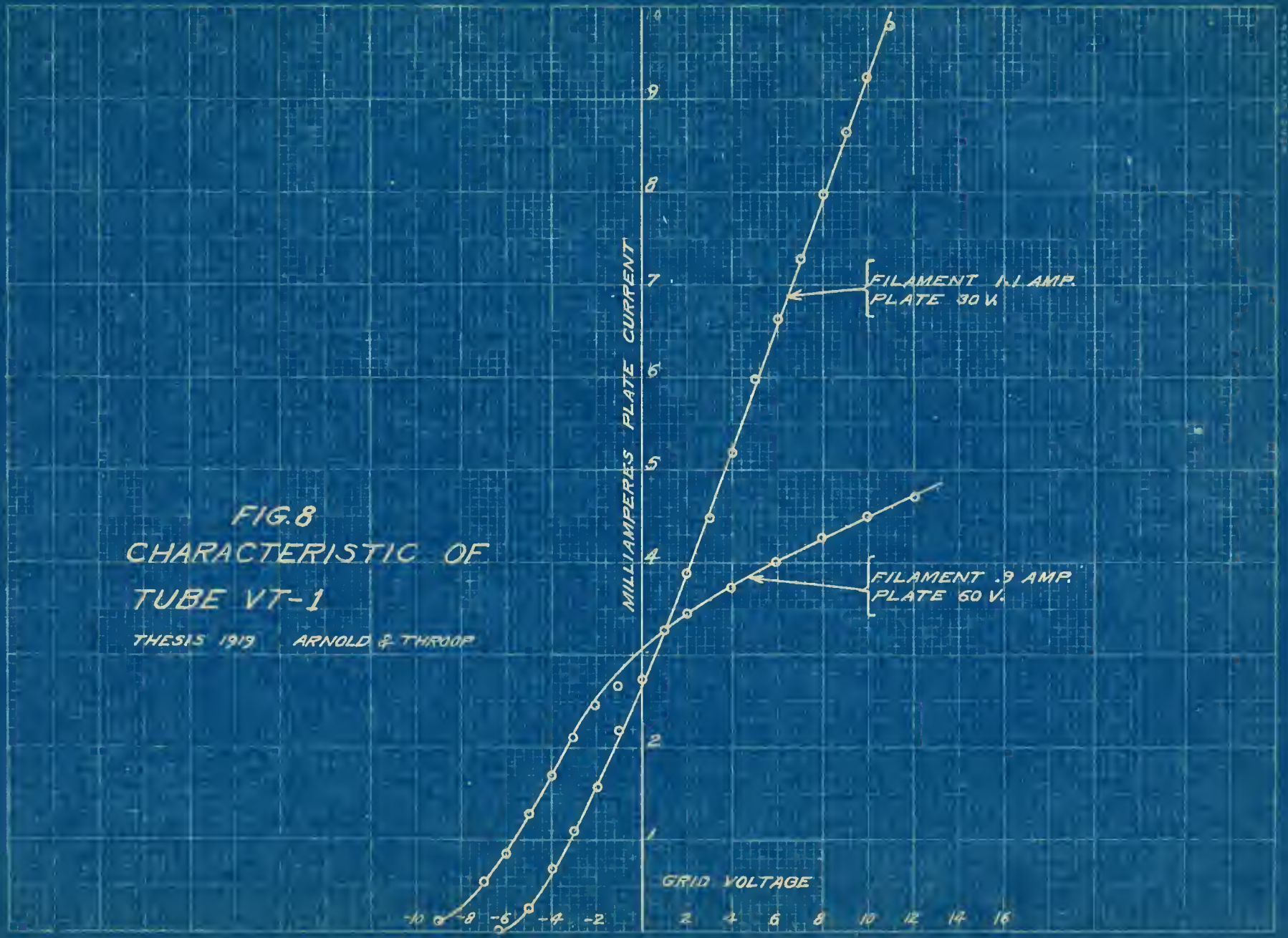

FIG. 8
CHARACTERISTIC OF
TUBE VT-1

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amperes and the plate voltage 30. If now the grid potential is increased negatively, a point is reached where the plate current is entirely arrested. In other words, the grid now has a sufficient negative charge to repell all of the electrons emitted by the filament and hence none is present between grid and plate and therefore no current can flow.

The amplification constant for this tube may be obtained from the curve. To produce a change of 3 milliamperes the change in plate voltage is from 62 to 92, or 30 volts. To produce the same change by grid potential requires a change from ½ volt to 5.2 volts, a change of 4.7 volts. Then $u = 30/4.7 = 6.4$. The power amplification must of course include the current relations, and since the grid current is very small, this constant approaches 200.

In Fig.9 we show similiar curves to the above for the VT-2, and again the specified values set down by the designers give the best working curve, which approaches a straight line.

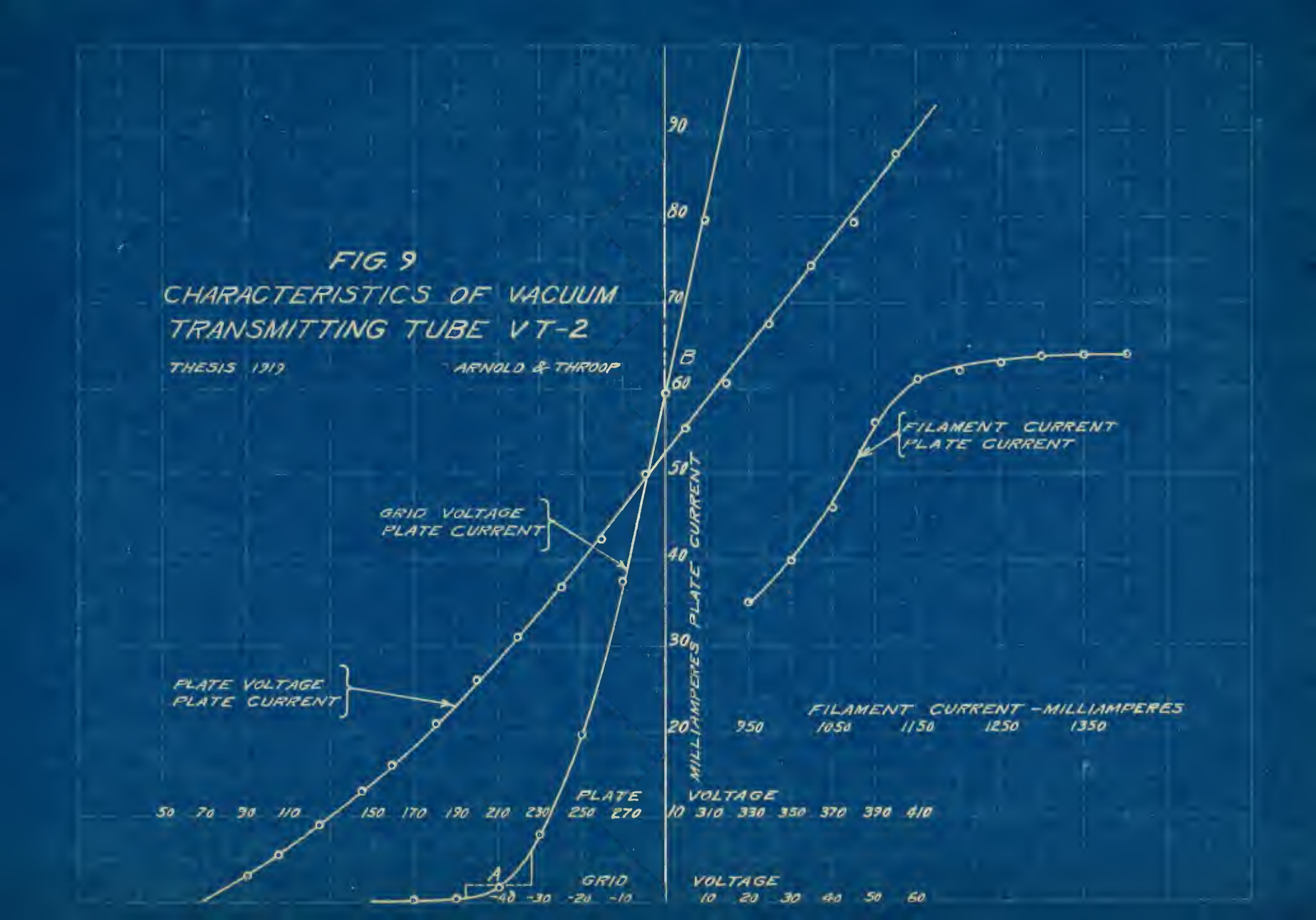
FIG. 9
CHARACTERISTICS OF VACUUM TRANSMITTING TUBE VT-2
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GRID VOLTAGE PLATE CURRENT
PLATE VOLTAGE PLATE CURRENT
FILAMENT CURRENT PLATE CURRENT
MILLIAMPERES PLATE CURRENT
90
80
70
60
50
40
30
20
B
A
FILAMENT CURRENT - MILLIAMPERES
950 1050 1150 1250 1350
PLATE VOLTAGE
50 70 90 110 150 170 190 210 230 250 270
GRID VOLTAGE
-40 -30 -20 -10
10 310 330 350 370 390 410
10 20 30 40 50 60

The point on the curve at which the tube is used depents upon what performance is desired. Referring to the VT-2 grid voltage-plate current cirve. If point A of the curve is used, that is, a grid potential of -40 volts, a decrease negatively of this voltage causes a greater change in plate current than does an increase. Hence, if the tube is used as a detector of radio frequency oscillations, and the grid potential is at A, the rise and fall of the incoming oscillations produces a similiar rise and fall in the plate current; but the amplitudes of the increase will be greater than the amplitudes of the decrease. Therefore a resultant pulsating uni-directional current flows in the plate circuit and charges a receiver condenser , which then discharges into the receivers once for each group of received oscillations.

If the tube is used in the region of point B, there is no difference in the changes of plate current for an equal decrease or increase of grid potential. Therefore we may use the tube at this

point as a repeater or relay. Amplification is here also obtained, for a fractional amount of energy impressed upon the grid circuit causes a large variation of energy in the plate circuit. This relaying action is possible both at audio and radio frequencies.

Generator Circuits

How such a tube may be used in a generative circuit will now be taken up. Fig. IO shows a tube circuit in which a source of alternating current makes the grid positive and negative. The plate current will follow the sine variation, but never reverses in polarity; from S of transformer T, a real alternating current may be drawn. The energy at S comes from battery B, while that used in the grid circuit comes from the alternator. If part of the energy at S could be turned back into the grid circuit and could be thus employed to do the exciting, it is evident the system would be self excited and would constitute an oscillating circuit. It is necessary that the energy turned back for exciting purposes have the correct amplitude and phase relation with regard to the plate current. The frequency depends upon the value of the inductance and capacity of the circuit. Fig. II shows such an oscillatory circuit.

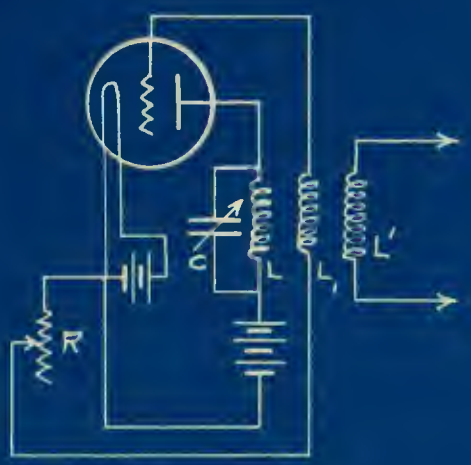

FIG. 11

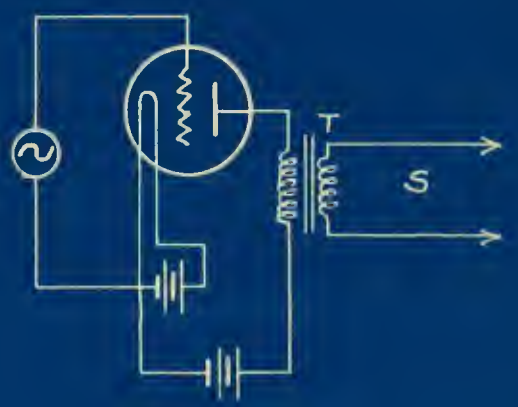

FIG. 10

VACUUM TUBE GENERATOR.

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The inductances L and L_I form the coupling between the plate and grid circuits, by means of which part of the energy is transfered back to the gridas excitation energy. The frequency of the undamped oscillations persisting in circuit C,L is determined by the values of capacity C and inductance L according to the equation $N = \frac{1}{2\pi\sqrt{LC}}$ cycles per second. The resistance R may be used to control the amplitude of the oscillations and to determine the rate at which the oscillations build up or die down. L' is the coupled inductance from which energy may be drawn to an external circuit for use.

The action of this self-excited generator system is illustrated in fig. I2. The curve is that of one of the VT-2 tubes used in this work. Below the curve is the e.m.f. - time curve for the increasing grid voltage, and on the right-hand side is shown the current-time curve. The dotted line is the average value of the current. It is now evident why the oscillating plate current reaches a maximum for the continuous oscillations. High frequency currents

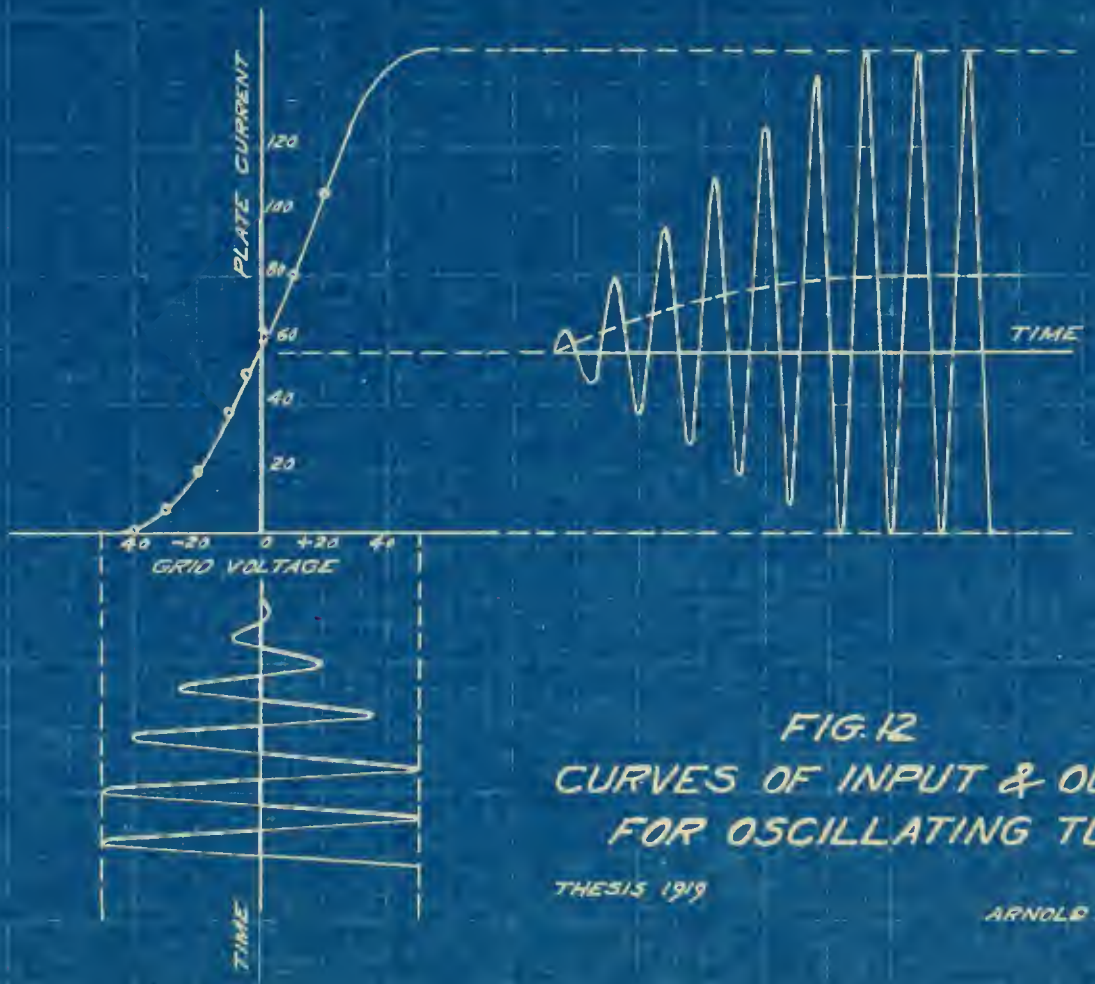

FIG. 12
CURVES OF INPUT & OUTPUT
FOR OSCILLATING TUBE.

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generated in this manner are not pure sinusoids but contain higher harmonics.

PART 3

From the discussion given on the operation of vacuum tubes as high frecuency generators, receivers and amplifiers, it seems very probable that they may be used in these capacities in the develoopement of a system of multiplex telephony.

The first problem is to determine to what extent speech frequency may be transmitted and received thru these tubes without distortion, and to what degree, in a qualitative way, waves of this fre - quency are amplified.

For the purpose of testing out and experimenting upon such circuits as would be developed in this investigation, a line of twisted pair No. 20 gauge wire was strung from the small Physics laboratory at the north end of the main building of Armour Institute to the room adjoining the instrument room at the south end of the building. A double pole double throw switch was connected at each end of the line, in order to throw either a local battery telephone circuit or a high frequency circuit on the

line.

The ordinary telephone circuit was used to talk over when making changes and adjustments on the circuits under test.

Repeater Circuits

The first attempt at the use of vacuum tubes in wire telephony was for the purpose of relays of speech currents; and to this end we developed the circuit shown in fig.I3. The transmitting circuit is shown at the left using a VT-2 tube; and the receiver circuit at the right using a VT-I. A telephone transmitter T was connected in series with the primary of a telephone induction coil L_1; the secondary of this coil L_2 being in the grid circuit and balanced by the 2mf condenser C_1. The grid was kept at a potential of plus IO volts. In this manner the grid potential is varied by the change in potential at the terminals of the secondary of the induction coil, which is due to the change in primary current resulting from the action of the transmitter.

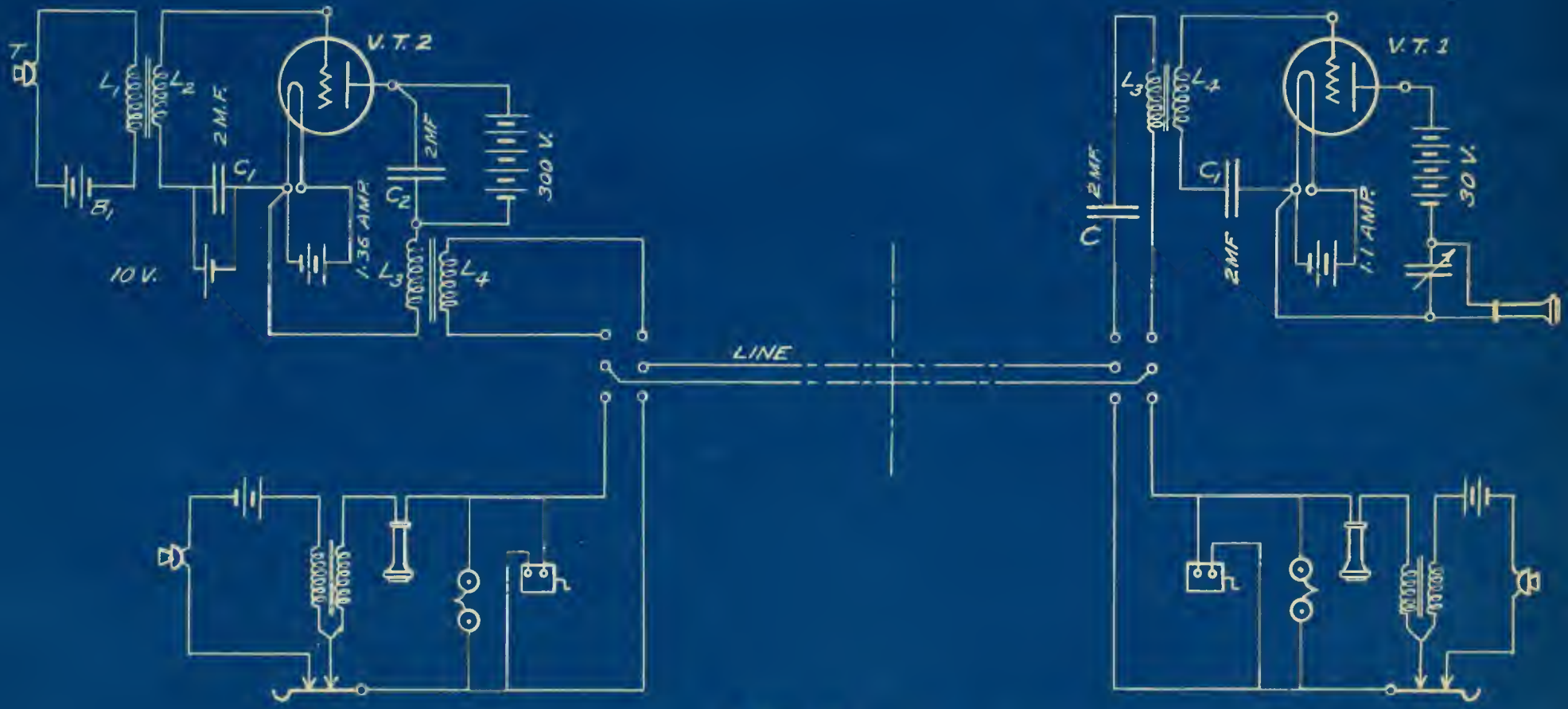

FIG 13

CIRCUIT ILLUSTRATING THE USE OF VACUUM TUBES AS TELEPHONIC CURRENT RELAYS

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The plate circuit consists of a 2mf condenser C_2 and the primary of a telephone induction coil L_3. The secondary, L_4, of this coil is in the line as shown. From what has been said, it is evident that speech currents in circuit T,L_I, B_I are repeated in an amplified condition in the line.

The receiving end of the line contains the primary of an induction coil L_3 and a 2mf condenser, which, added to the line condensance balances roughly the line. The grid circuit of the VT-I tube is coupled to the line thru the secondary of the induction coil L_4 and is balanced by condenser C_I. The receiver plate circuit contains only a receiver in addition to the 30 volt battery supplying potential to the plate.

The tubes were operated with normal operating values and under the conditions outlined above. Ordinary speech was amplified to such an extent that the words could be heard and understood at a distance of three feet from the telephone receiver. Furthermore, speech was found to be very much more clear and free from distortion than that received

by means of the local battery telephone.

High-Frequency Circuit

Having thus proved that a vacuum tube can amplify and repeat telephonic currents, functioning either as a transmitter or as a receiver, not only without distortion, but with increased clearness; the next step undertaken was the design of a high-frequency circuit. The first success was obtained with the arrangement shown in Fig. I4.

Here the local battery telephone circuit was permitted to be permanently connected to the line as well as the high frequency circuit. The transmitter circuit consisted of a vacuum tube generator upon whose high frequency output was superposed variations at voice frequency. The frequency of this generator system is determined by the values of C and L. The condenser C is variable and of radio frequency dimensions, that is, a capacity varying from .00005 to .00096 microfarads. The inductance coil L is made up of a circular coil of rectangular

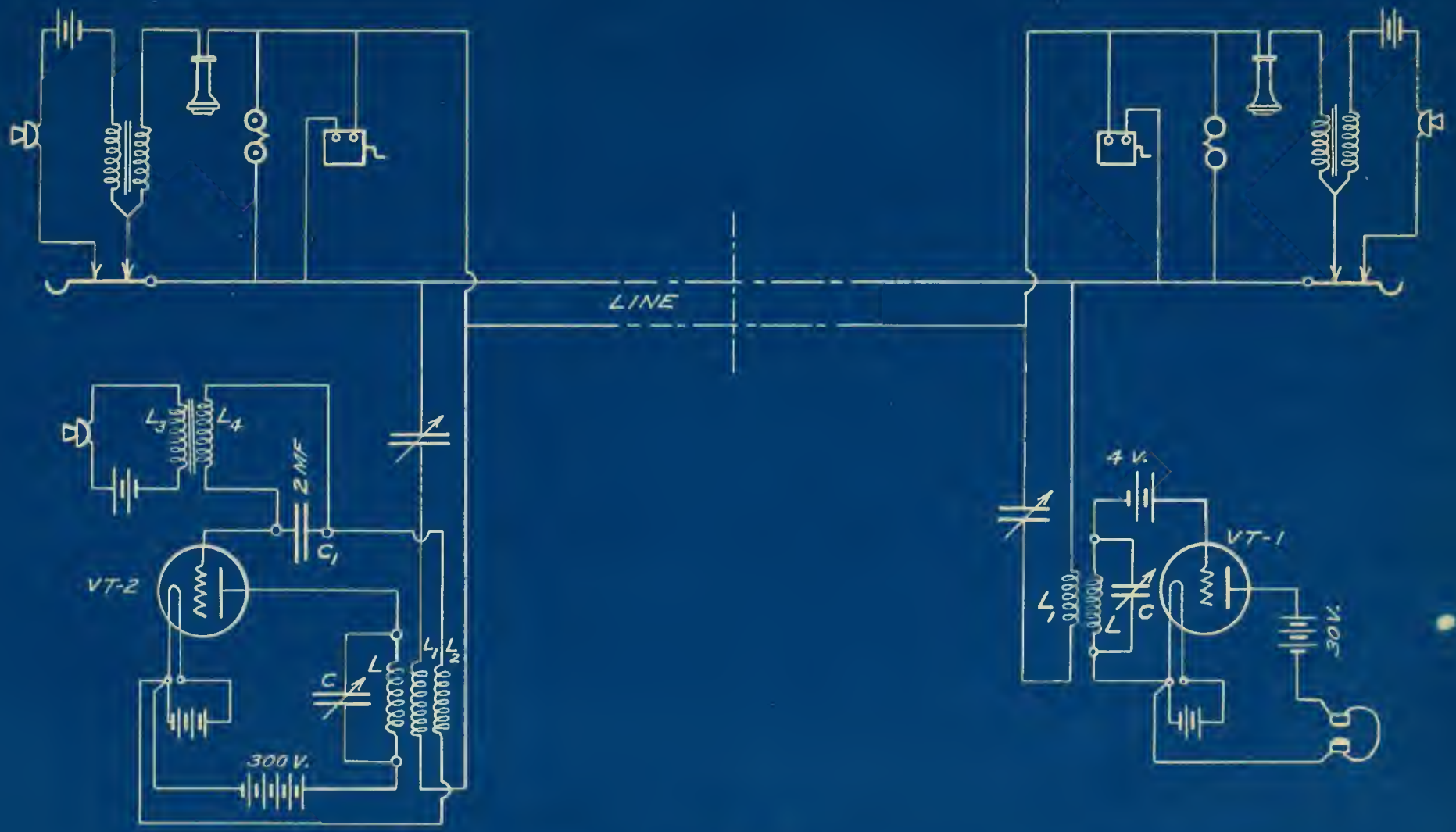

FIG. 14
MULTIPLEX TELEPHONE CIRCUIT EMPLOYING FREQUENCIES OF ZERO & 100,000 CYCLES PER SECOND

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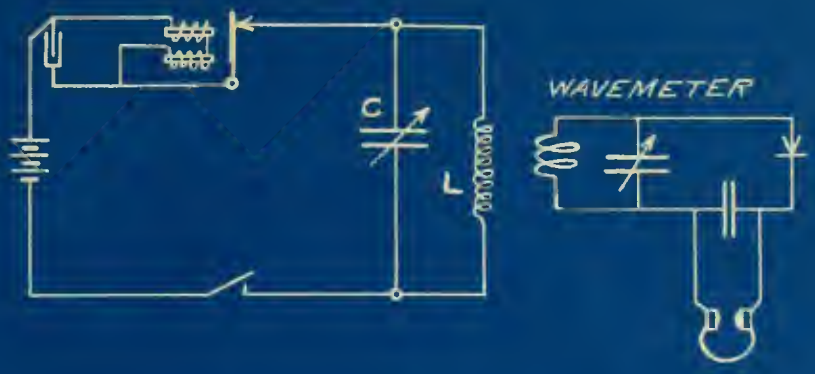
cross section as shown in Fig. 15. The coil has 40 turns of No. 20 double silk covered wire, and a measured inductance of .575 millihenries. The grid circuit is coupled to the plate circuit by the coil L_2. Condenser C_I permits the high frequency oscillations to pass around the telephone induction coil L_4. The line is coupled to the oscillating circuit by means of L_I. The grid potential of 300 volts was obtained from storage batteries.

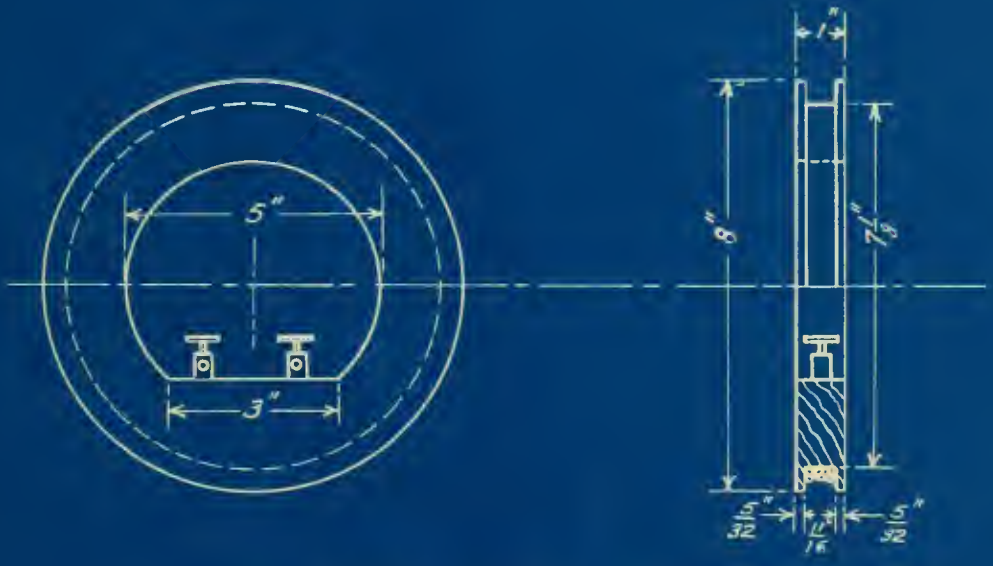
The frequency of the receiver circuit is also determined by C and L; L being coupled to L_I of the line. The tube operates as has already been explained for tubes in a receiver circuit. The plate potential of 30 volts was obtained from 15 cells of flashlight battery connected in series.

The oscillating circuits of the receiver and transmitter are adjusted to oscillate at the same frequency. The line is then adjusted by means of the variable condenser to approach this frequency also. It is easy to know when the two circuits have the same constants, for if they oscillate at different frequencies, a beat tone will be heard which has a



MEASUREMENT OF HIGH FREQUENCY.

FIG. 16



INDUCTANCE COIL

FIG. 15

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frequency equal to the differnce between the two circuit frequencies. This differnce may be beyond audibility and to be sure that such a condition does not exist, the condensers should be varied until a note is heard, and then further adjusted until the note disappears at the lower limit. When this point is found it is possible to bring in a low pitched sound if the moveable plates of the condenser are turned slightly to either side. The receivers used were of the high resistance type commonly employed in wireless telegraphy.

With this circuit a two-way conversation was held over the local battery circuit, and a one-way conversation over the high frequency apparatus. Absolutely no interference or distortion was detected after the beat note had been tuned out. The words received over the oscillatory circuit were clear and distinct and as strong as ordinarily produced by a common battery telephone. The frequency of the oscillatory circuit was 100,000 cycles per second, as measured by a wavemeter of the ordinary radio type.

In Fig. I6 we show how this measurement is made. A wavemeter consists of nothing more than a fixed known inductance and a variable condenser. Fastened to the turning head of the condenser is a pointer which indicates upon a circular scale the wavelength of the oscillation for which the inductance and setting of the condenser are two of the constants. To measure the natural frequency of the circuit C,L, the circuit is excited by a buzzer so that with each make and break a train of oscillations are set up. If now, the coil of the wavemeter is brought up near to L and the meter condenser adjusted until the loudest sound is heard in the head telephone, the point of resonance of the two circuits is indicated and the reading of the meter condenser shows the wavelength of the oscillations in C,L. The frequency may then be calculated from the equation $V = f\lambda$. In which V is the velocity of light and the highest velocity attainable by an electric current, 300,000,000 meters per second. The wave length is read on the condenser and f solved for in cycles per second.

Combination Multiplex Circuit

Since the VT-2 Tube will function as a receiver as well as a transmitter it seemed possible that the tuned circuit of the transmitter could also be used as the selective circuit of the receiver. After a number of schemes were tried out with various results, the circuit shown in Fig. I7 was devised.

It is a combination receiving and transmitting circuit using only one tuned circuit, L,C. One of the features of this arrangement is the series connection of the inductance L and condenser C, the circuit being completed thru the plate and filament. Another is the plate pressure connection. On other circuits the 300 volt supply was in series with the oscillating circuit, but here it is bridged thru iron core reactances. The success of this arrangement makes possible the use of one source of potential for a large number of circuits, since the high frequency cannot pass thru the impedance. The idea of bridging a potential in this manner was first used by Colpitts, of the Western Electric Company,

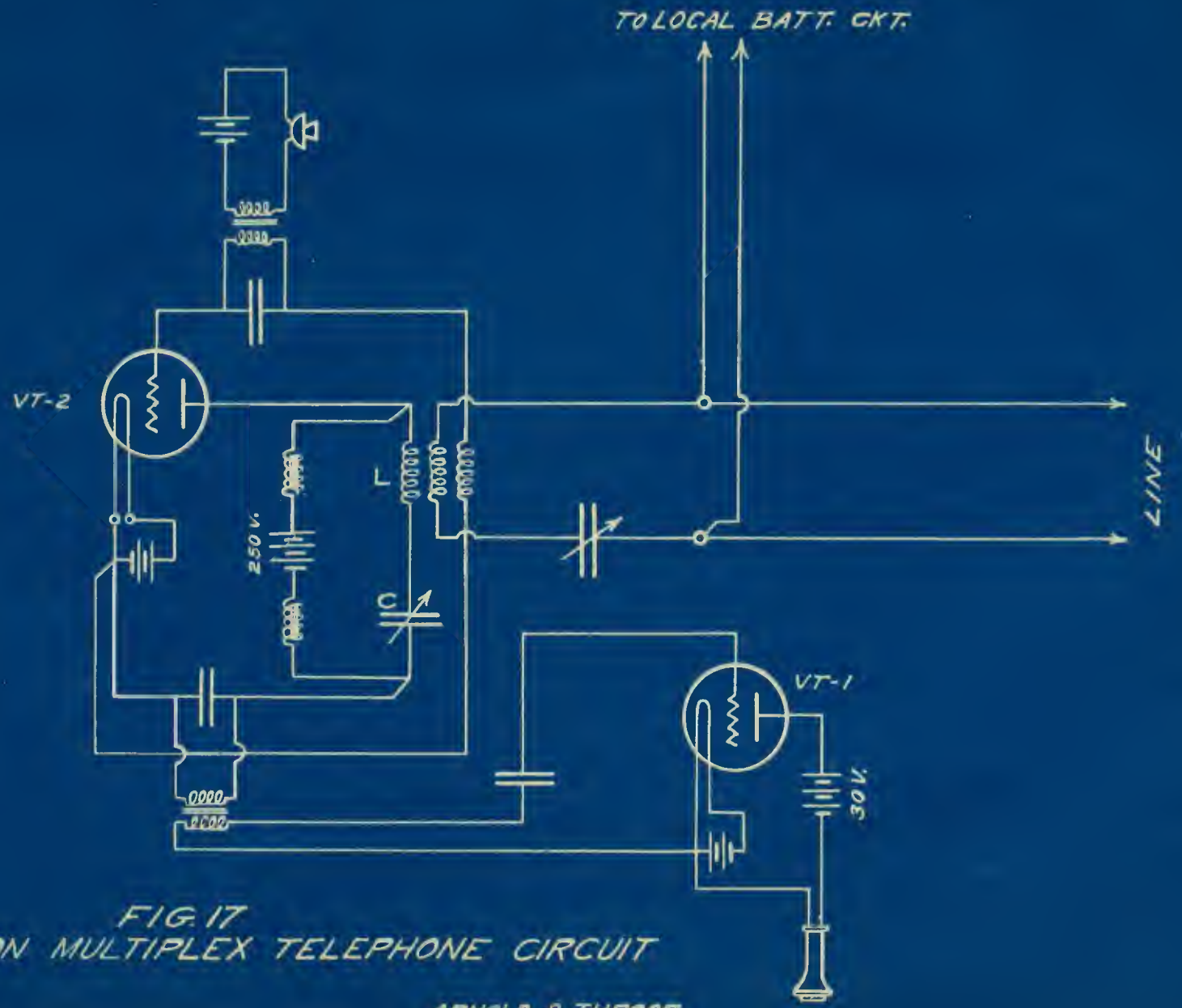

FIG. 17
COMBINATION MULTIPLEX TELEPHONE CIRCUIT

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in an oscillating circuit for wireless telephony.

The secondary of the transmitting induction coil is fed into the grid circuit as in the other circuits already discussed, while the receiver is tapped into the plate circuit in a similiar manner. The secondary of the receiver induction coil is balanced by a 2mf condenser in series as shown. The plate circuit of the VT-I contains only the high resistance telephone receiver and a 30 volt battery.

When a balance of frequencies was obtained with this circuit a two-way conversation was held without interference with the local battery circuit. No distortion was noticeable.

It must be remembered that while the circuit C,L was absorbing the modulated high frequency energy from the line, that circuit itself was oscillating by virtue of the valve action of its own VT-2 tube. Now, if the incoming modulated wave is of the same frequency as that being continuously generated, the two will combine in a manner determined by the phase relation of the waves.

If the phase relation were 180^{o} the incoming wave would either be entirely nullified or else severe distortion would probably result. Neither of these objectionable conditions were encountered except in the case of certain changes in frequency of one of the circuits. Evidently then there must have existed a kind of pulling into phase of one circuit by the other, similiar in general to the pulling into phase of two alternators when running in parallel.

The chief criticism of this arrangement lay in the fact that, while the received words were distinct and clear, they were not loud enough. This may have been due to the use of old and inferior telephone transmitters, or to the VT-I circuit. The receiver used was of the radio high resistance type.

An attempt was now made to devise a circuit similiar to Fig. I7, but using standard common battery desk telephone equipement. It was also desired to increase the loudness of the received message.

The result in this direction is shown in Fig. I8. The transmitter is of the regular common

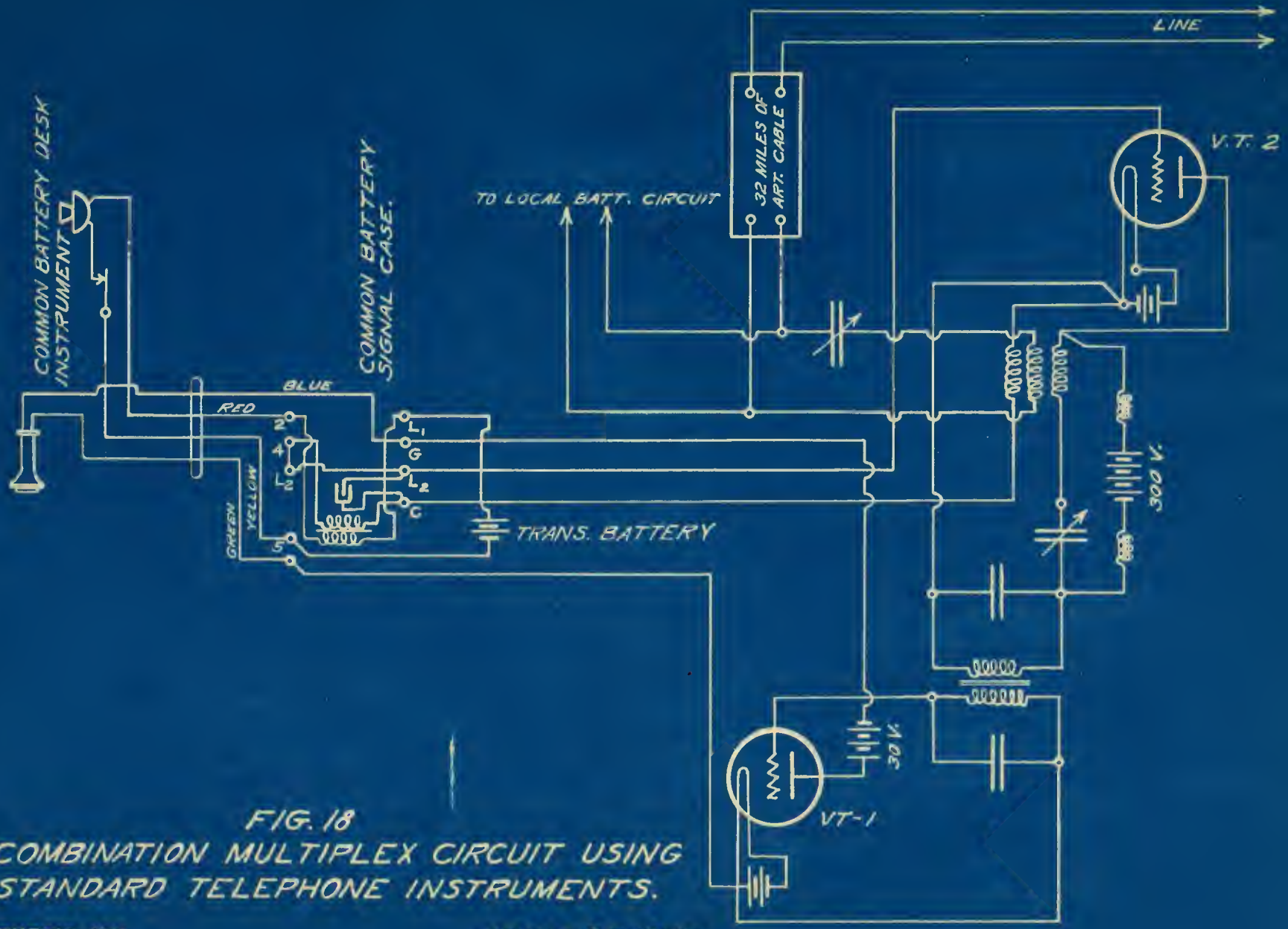

FIG. 18
COMBINATION MULTIPLEX CIRCUIT USING STANDARD TELEPHONE INSTRUMENTS.

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battery desk stand type, as is also the receiver. The change made in the circuit is in connecting the 2mf condenser, formerly in series in the grid circuit of the VT-I, in parallel with the secondary of the receiving induction coil. The induction coil and 2mf condenser in the signal case were used in the transmitter circuit. The transmitter was given its normal operating current of 100 to 150 milliamperes. The inductance coils had 80 instead of 40 turns.

This circuit when tried out on the experimental line, with the local battery instruments connected in, showed better results than any of those preceding. As before mentioned, the receiver was of low resistance, and therefore did not approach the radio receivers in sensitiveness. Yet, speech was remarkably clear and distinct, and sufficiently loud.

To further test this circuit, a Leeds and Northrup 32 mile artificial cable was connected into the line. The circuits were tried in this way without any adjustment of the line condensers, and as would be expected, distortion was quite pronounced. An adjustment of the line capacity however, cleared

and balanced the circuit and conversation was again possible with the same results obtained with the short laboratory line. The frequency employed was I25,000 cycles per second, small capacity being used in the oscillating circuit.

The detail of changes in connections in the pedestal and signal case of the common battery instrument is shown in fig. I9. The result is that the receiver is connected to two strands of a four conductor cord, and the transmitter also to two strands thru a contact of the switch in order to cut off the transmitter battery when not inuse. The signal case required only a jumper to connect one of the secondary sides of the coil to one side of the condenser. The markings are intended for use in common battery telephone work, and have no significance here.

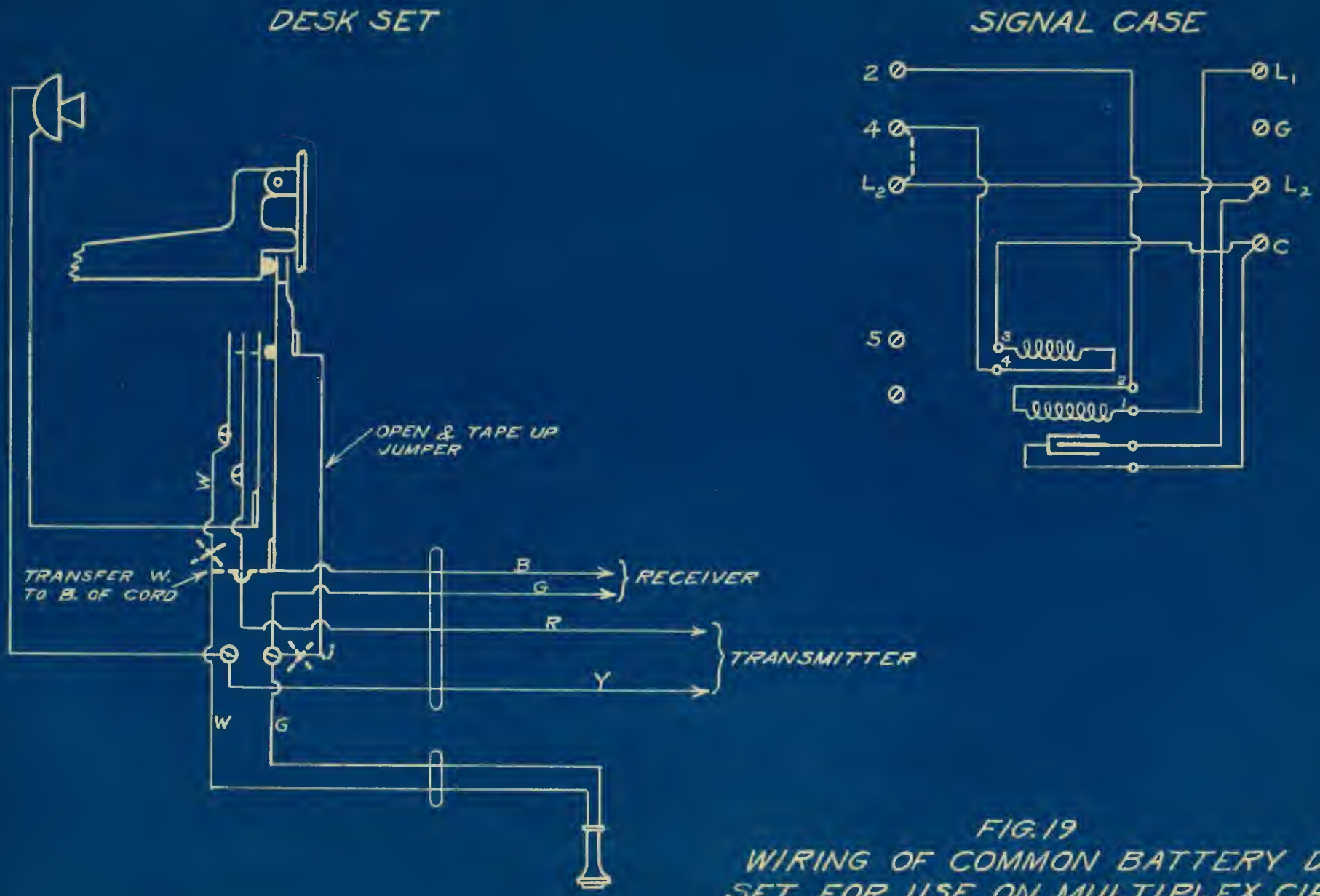

FIG. 19
WIRING OF COMMON BATTERY DESK SET FOR USE ON MULTIPLEX CIRCUIT.

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Four circuits, as shown in fig.18, were now connected to the line in order to build up a three-circuit multiplex system. The general arrangement was as shown in fig. 21. In two of these circuits 80 turn coils were used with full condenser capacity; in the other two, 40 turn coils with the condensers set at their lowest reading. This gave the maximum difference in frequency between the two complete circuits. The set of lower frequency was first adjusted and tuned for the best transmission and reception of speech. Then the set of higher frequency was adjusted for best results. The two complete oscillating sets were then closed down on the line together. The first effect was to unbalance the setting so that distortion was very pronounced in both, and also to bring in beat tones which were not present before in the separate sets.

It was found that the circuits had become very sensitive to condenser adjustment, a slight change brought in beat tones from the lowest to the highest pitch. Permitting the two to be connected together in this manner, we proceeded to retune each

circuit for the best transmission and to eliminate the beat tones. This was accomplished, and the sets operated in this manner as well as alone.

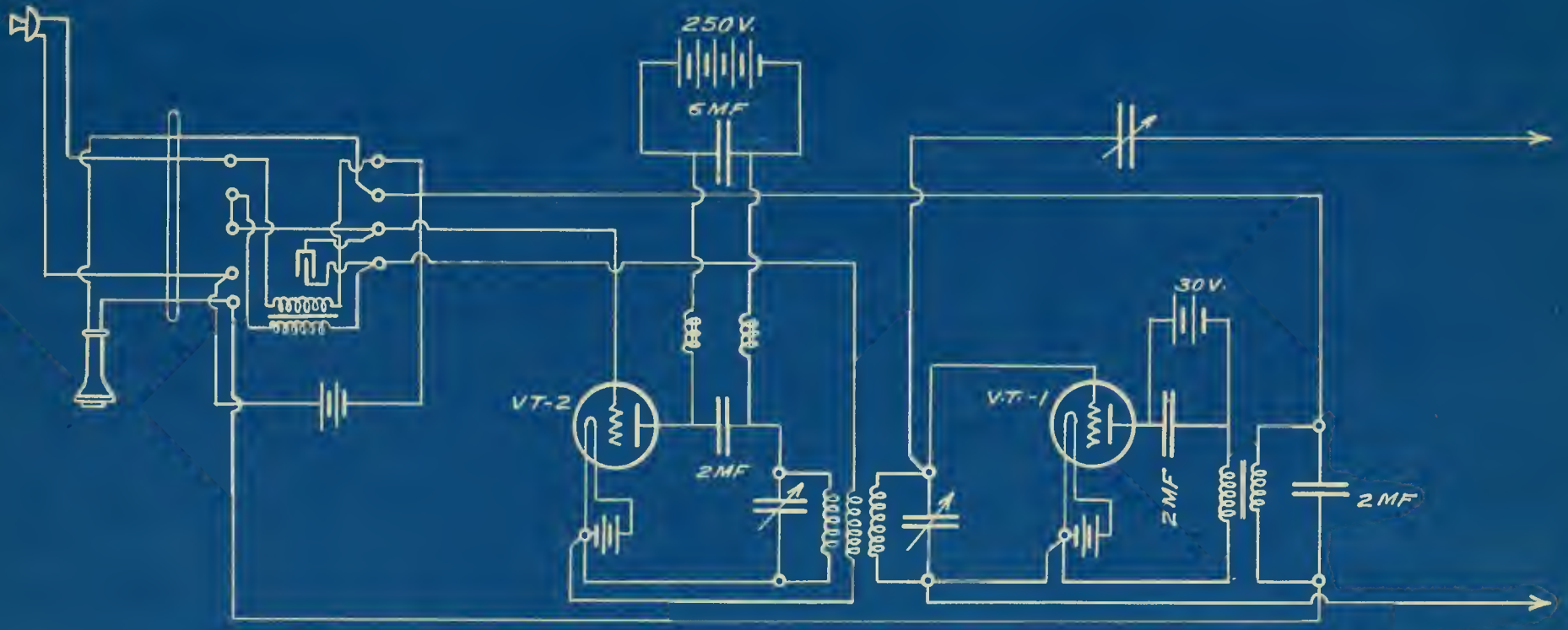
To test and adjust for interference between the two sets was thenext step. The first trial with the last adjustments showed cross-talk between the two, so we proceeded to tune one set out of the other; at the same time preserving the quality of transmission already gained. After extended trials of adjustment and measurements of frequency, it was found impossible to entirely eliminate cross-talk, although it was reduced to a degree comparable with the cable induction often experienced in the ordinary systems of telephony.

To further eliminate this interference the coils of the oscillating circuits were enclosed in sheet metal cans. The result of this proved that part of the cross-talk came from radio transmission and reception thru the air; for interference was cut down to about half of its last value. Continued effort on this circuit seemed to indicate that an adjustment fine enough for this work could not be

obtained. Our efforts were now turned toward devising a new circuit which would respond only to frequencies intended for it, and which would give the same quality of speech transmission as possessed by the one to be abandoned.

An entirely new scheme was decided upon; a combination circuit employing two tuned circuits instead of one. The result is shown in fig.20. The transmitting and receiving portions each have their own tuning; and the inductance coil of the receiver is also made the line inductance coil to absorb the energy to be transmitted. In this way the received energy passes directly into the receiver circuit. It was also found that shunting the 250 volt plate battery with a capacity of about 6 microfarads increased the quality of transmission.

Four circuits of this type were now connected into the line as shown in fig.2I. Each set was adjusted to give the best transmission, and the two then closed down together. This immediatly threw both out of adjustment, caused considerable distortion of speech, and brought in beat tones. To meet



COMBINATION ARRANGEMENT USING TWO TUNED CIRCUITS.

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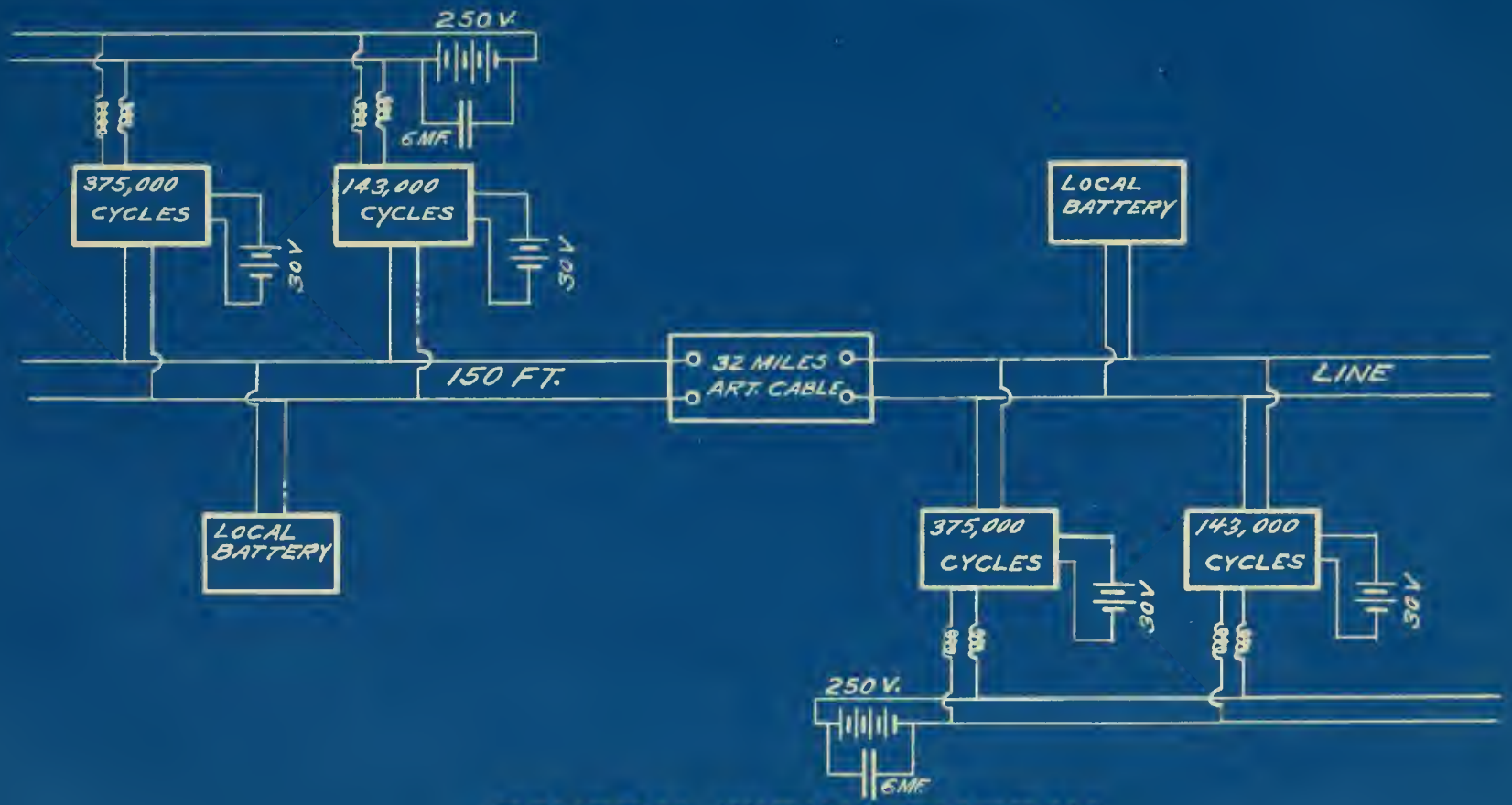
FIG. 20



GENERAL WIRING DIAGRAM

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FIG. 21

the new conditions we adjusted the 40 turn set until all beat tones were cleared, then brought in best speech transmission by means of the tuned receiver circuits, at the same time removing the beat tones with the line condensers. We then did the same with the 80 turn circuits. Thus far,both met all requirements and were ready to be tuned for cross-talk.

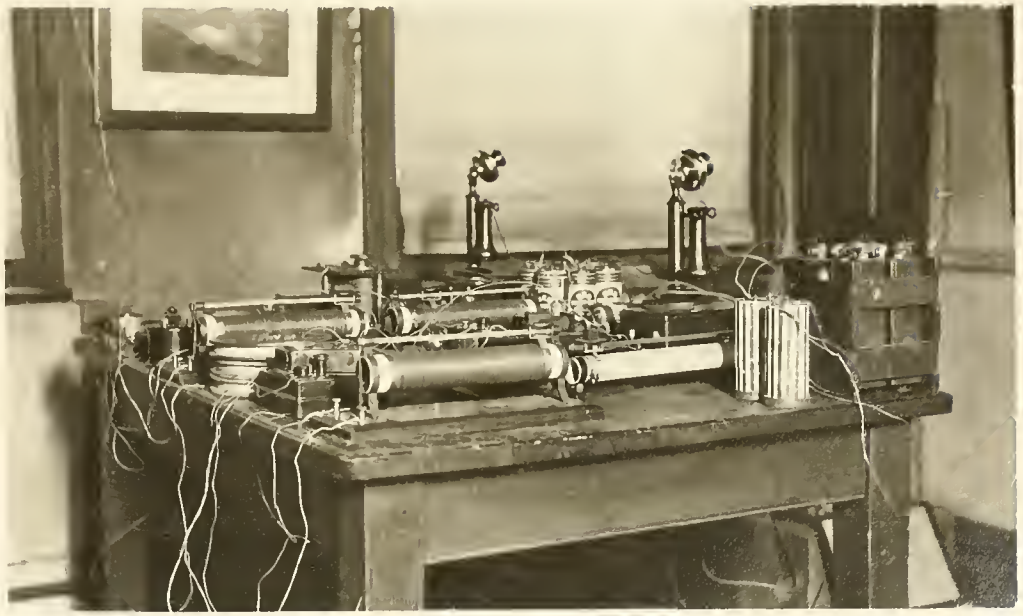
The first trial gave interference of about the same magnitude as that resulting in the first circuit. The 80 turn circuit was now adjusted by means of the receiver and line condensers until absolutely no interference whatever came from the 40 turn set. The other 80 turn circuit unfortunately had to be dismantled in order to release storage batteries and rheostates which were needed for other tests in the laboratory.

That this circuit filled the requirements, and that a three-circuit multiplex system had been accomplished was, however, proven. With conversations goin on over the common battery line and over the 40 turn circuit, the 80 turn circuit could be brought in or out by adjustments of the line and receiver condensers.

Beat tones were eliminated when this final setting was accomplished, and conversation proceeded with the quality and loudness ordinarily obtained with a common battery telephone.

A wavemeter was now placed in inductive relation to each of the circuits. The condition indicated was very satisfactory; for the two circuits which were adjusted for best transmission, each showed a wavelength of exactly 800 meters. The other 80 turn circuit showed a wavelength of 2100 meters. These wavelengths are indicative of frequencies of 375,000 and 143,000 cycles respectively.

The diagrams which accompany this discussion do not show the potential and current rheostates, meters and auxilliary equipment necessary in the experimental circuits. The photographs show the apparatus for the two and three circuit arrangements. In each of them some of the important pieces of apparatus are seen.



Apparatus at South End of Main Building,

Armour Institute of Technology.

Three-Circuit Equipment at South End of Main Building.

Three-Circuit Equipment at North End
of Main Building.

CONCLUSION

That a high frequency current may be employed as well as a direct current as a carrier of electric waves of speech frequency has been conclusively shown. It has also been demonstrated that at least two independent high frequency circuits may operate simultaneously on the same pair of wires without interfering with one another; and further, that high frequency and direct current carrier circuits may be operated simultaneously without interference. All of these results have been accomplished by means of vacuum tube oscillators and receivers.

One of the difficulties encountered in all of the circuits used, was the elimination of beat tones. No time was spent in investigation the origin of these interferences, but it is known that they are the result of the simultaneous exictence of two waves which differ in rate by an audible frequency. In our work we employed circuits which differed by at least 100,000 cycles at all times, and yet beat tones were present.

The answer is probably in the explanation of the wave form of the high frequency current of the vacuum tube oscillator. As was pointed out, the vacuum tube oscillating circuit does not generate a sinusoidal current wave. Since higher harmonics exist in all of these circuits it seems very possible that the beat tones came from the difference in frequency of the various higher harmonics. The value in this work, of a high frequency generator of a sinusoidal wave, is at once evident. But we believe that these low frequency beats can be eliminated by some circuit arrangement; and that vacuum tube oscillating circuits may be employed.

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